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Diode-Pumped Solid-State Laser Drivers For Inertial Fusion Energy

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Introduction

An ultimate goal of inertial confinement fusion (ICF) studies is to build a power plant based on fusion.[1] The top-level requirements for the laser driver are suggested to be:

- Efficiency, > 5 %
- Reliability, availability and maintainability, > 10^9 shots
- Cost, < \$1.5 B
- Beam smoothness for direct drive, < 1% on-target for < 1 nsec
- Wavelength, < 0.4 μm

The efficiency of the inertial fusion energy (IFE) driver is important, since, together with the target gain, it determines the recycled power needed for the driver. The reliability and cost requirements follow from the need to produce commercially attractive electric power with a minimum 30-year plant lifetime. The beam smoothness and wavelength requirements derive from 25 years experience in laser fusion, which have been reviewed in recent papers on direct drive[2] and indirect drive.[3]

Flashlamp-pumped solid state lasers

When Elias Snitzer first doped neodymium laser ions into a crown silica glass in 1961 and demonstrated that this optical material could generate laser action, the opportunity for producing large-size gain media was born. It was soon realized that Nd:glass offers many attributes ideally suited to the requirements of an ICF laser. Since the "Janus" flashlamp-pumped Nd:glass laser was built in the mid-1970's at LLNL, there was a belief that a scalable architecture had been identified, for which millisecond-regime flashlamp-pumping could be employed to generate the needed coherent nanosecond pulse to irradiate the target. Essentially, the Nd:glass gain medium serves as a "brightness-converter" for the flashlamp energy, in time and in space.

Flashlamp-pumped Nd:glass lasers have served to unravel the physics of ICF during the last two decades, during which time a series of the lasers have been built around the world and in the United States. During this period, these lasers continued to improve markedly in many ways. For example the damage threshold of Nd:glass was increased from ~2 J/cm^2 to 20 J/cm^2 for nanosecond pulses, a new multi-pass architecture was developed based on the invention of the "plasma electrode Pockels cell," surface finishes on optics were improved greatly, and the amplifiers became "bundled," (i.e. 8 apertures located within the same pump chamber). The pumping and extraction efficiencies were optimized, and the part-count and footprint were minimized. Beam propagation came to be understood, so that the constraints of nonlinear effects and aberrations could be reliably managed. Frequency-conversion to short wavelength, and, more recently, beam-smoothing were developed. This effort now will culminate with the building of the National Ignition Facility, for which the prototype beamline and the beam bundle architecture have been validated in the Beamlet (Fig. 1) and AMPLAB facilities. Flashlamp-pumped solid state lasers built for ICF studies have been optimized for the \$/Joule figure-of-merit and for their ability to match the target requirements. They are inherently single-shot devices, requiring hours to recover from thermal distortions. The goal of developing ICF lasers with high repetition rate and efficiency has not yet been significantly addressed. The main problems are that the glass slabs cool very slowly, the flashlamps have limited lifetimes of $< 10^5$ shots, and the gain medium stores energy for a relatively short time (0.3 msec).

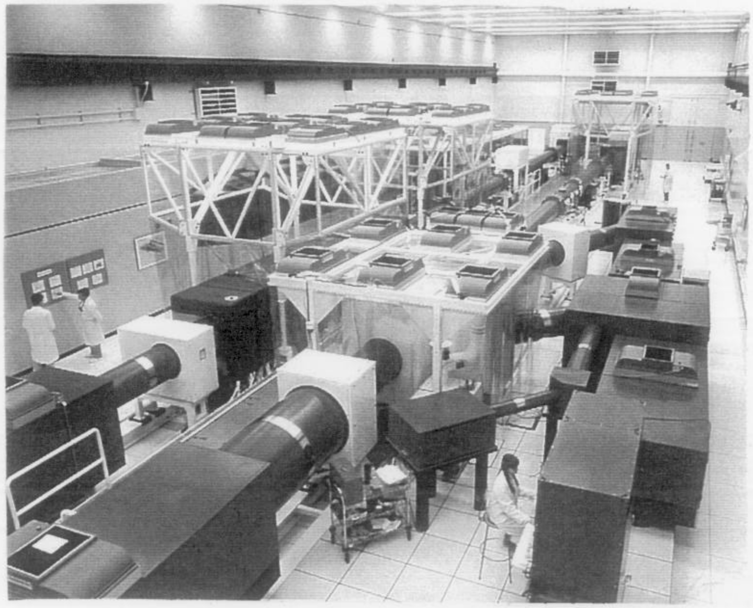

Fig. 1: Beamlet facility used to validate beam propagation to the target.

Diode-pumped solid state lasers (DPSSLs)

Gas-cooled diode-pumped crystal lasers are envisioned to be the next generation ICF solid state laser system. NIF and the advanced DPSSLs proposed herein share a great deal of common features, especially with regard to fundamental issues relating to multi-pass amplifiers, laser propagation, energy storage, extraction, pumping, linear and nonlinear wavefront distortions, frequency-conversion, and beam-smoothing. The DPSSL approach builds on the last two decades of solid state laser development but also adds several imposing challenges -- efficiency, repetition rate, reliability, beam-smoothness, and cost. Solutions to these issues have been proposed by:

- employing near-sonic helium cooling of the laser slabs
- trading the flashlamps for low-cost, large-size laser diode arrays
- using laser crystals with greater energy storage and thermal conductivity than Nd:glass
- deploying two-dimensional smoothing by spectral dispersion (2D-SSD)

The Mercury Laser, discussed below, is the first step in integrating these new approaches, and in producing new capabilities for irradiating ICF targets. These new facilities with rep-rated capability will also provide a paradigm-shift for experiments and measurements in high energy density physics.

Mercury Laser

We are in the process of developing and building the "Mercury Laser" as a first integrated demonstration of a new generation of DPSSLs for inertial confinement fusion and high energy density physics, see Fig. 2 below. Mercury will be the first demonstration of a scalable solid-state laser architecture compatible with advanced ICF goals, constructed at ~10% of the optimal transverse-limited aperture-area of $(\sim 15\ \mathrm{cm})^2$. Primary performance goals include 10% efficiency, 10 Hz repetition rate, 2 nsec pulsewidth, and energies of 100 J at 1.047 microns. It is noteworthy that this energy is the same as that of the Janus Laser, based on flashlamp-pumped Nd:glass and originally built in 1973. Also of interest is Mercury's capability for $2\omega/3\omega$ frequency conversion, for reconfiguring the system for picosecond-pulse generation, and for ultra-smooth beam operation. When completed Mercury will be the highest energy/pulse diode-pumped laser ever built by an order of magnitude.

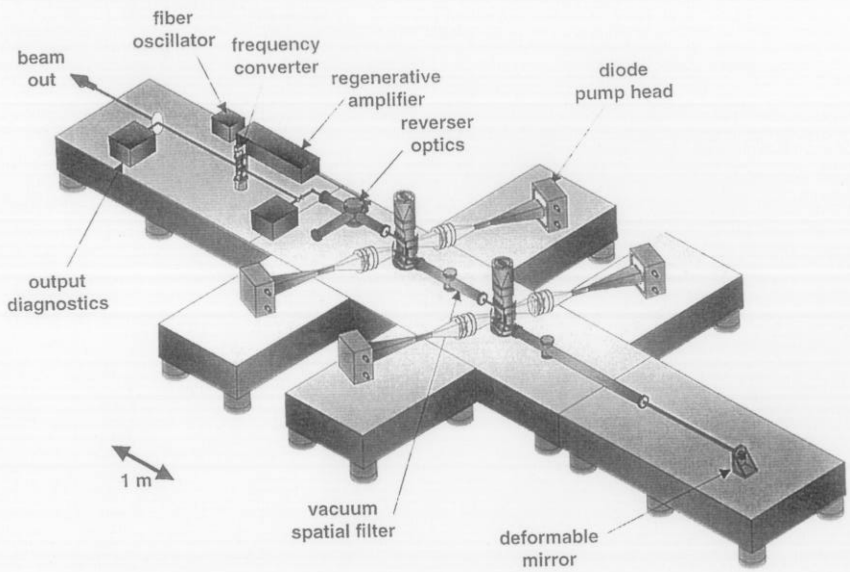

Fig. 2: Conceptual diagram of Mercury laser system.

Many advanced laser technologies are being incorporated into the Mercury laser. Laser diode arrays represent an enabling technology for realizing solid-state lasers for ICF, see Fig. 3. Not only are the diode technical performance specifications such as brightness more demanding than what is currently available, the diode array manufacturing costs will eventually have to be reduced by an order of order of magnitude. The goals of the crystal growth efforts for the Mercury project are to produce high quality Yb:S-FAP [Yb^{3+}:$Sr_5(PO_4)_3F$] crystals to serve as the gain media. The Mercury Laser head and gas cooling architecture are being designed in a modular format, in which the laser slabs are mounted in individual vane elements supporting the gas-flow. The vane elements are then stacked to form the laser head assembly. Between each of the flow vanes is a cooling channel to remove the waste heat from the laser slabs. Importantly, this cooling technique is scalable to much larger aperture-size and hence larger energy/pulse. Gas-cooled laser architectures offer the promise of good beam quality due to minimal thermal distortion[4,5] simultaneous with other essential parameters such as high peak power, rep-rated operation, high wall-plug efficiencies, and adequate beam smoothness.

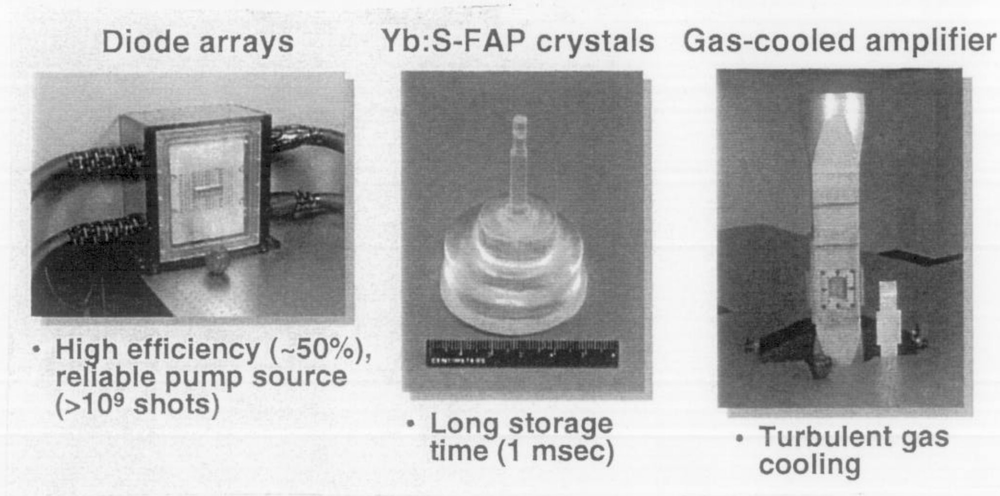

Fig. 3: Mercury gas-cooled amplifier, laser crystal boule, and diode array.

ICF lasers beyond Mercury

The critical milestones of ICF lasers after Mercury should relate to the readiness of the diode-pumped solid state laser driver to proceed to the next stage and then to inertial fusion energy (IFE). The reliability, availability and maintainability of the laser components should be deemed to be acceptable for an "integrated research experiment" or IRE (kJ-class laser coupled with average-power target chamber), and have a plausible means of attaining the driver requirements of IFE as enumerated above. It is thought that addressing the IRE requirements will suggest a clear pathway to IFE for most issues, although the diode cost reduction will demand special attention. Development goals can be summarized as follows:

- Efficiency — Increase the efficiency of the DPSSL IFE driver to between 10 to 20 % by addressing improvements throughout the system, for example by enhancing the overall brightness of diode arrays by a factor of 4 (2x in power, 2x in brightness) for improved pumping efficiency, and by reducing thermal edge effects with corrective optics.
- Diode cost — Reduce the cost of laser diode arrays to $0.50/Watt for the IRE and define a pathway to $0.07/Watt or less for IFE.
- Beam smoothness — Devise and demonstrate a scheme to produce < 1% smooth irradiation on-target for direct-drive, probably with smoothing by spectral dispersion.
- Gain media — Select and grow gain media with > 10 cm aperture and fabricate into laser slabs with suitable optical quality (< 4 nm rms distortion for 0.002-2 cm spatial wavelengths).
- Frequency conversion — Demonstrate high-average-power frequency conversion at high efficiency (80%) employing the gas-cooling techniques, and with suitable bandwidth.
- Wavefront correction — Produce beam quality of < 5x diffraction-limited using active and passive wavefront correction during average-power operation.
- Technology integration — Demonstrate integrated performance of DPSSLs to assure engineering viability with reliable operation, including the front-end, wavefront control, gas-cooling, extraction, beam-smoothing, and diode arrays.
- Average-power target chamber — Develop approaches for a survivable target chamber where x-ray yields lead to significant but manageable surface ablation.
- Scalability — Resolve the manner in which multiple apertures and beam bundles are assembled to attain the kilojoule and megajoule level.

One possible vision of an IRE based on a 4 kJ DPSSL follows in Fig. 4. This laser system would test performance at gain-limited aperture size and incorporate the multi-aperture bundling needed to scale to very high energy.

The IRE must be sufficient, together with the NIF and other supporting experiments in the IFE program, to provide confidence to proceed to an average power fusion demonstration. The role of the NIF can be to test the physics of direct drive targets, as well as to examine chamber clearing rates and target debris migration to final optics, and the effect of xenon gas fill. The vision of an IRE is pictured in Fig. 4, where an average-power x-ray source can be used to test first-wall and final-optic survivability for IFE. In addition rep-rated shock and plasma physics experiments and x-ray imaging could be performed for national security. Another possibility, somewhat more speculative, is to develop a laser-based neutron source using high intensity pulses from the laser. Exercising the short-pulse option and multiple target chambers on the IRE can usher in a breadth of applications. Thus the proposed DPSSL IRE would address issues relevant to advanced lasers for direct and indirect drive for energy, and provide a platform for experiments relevant to national security.

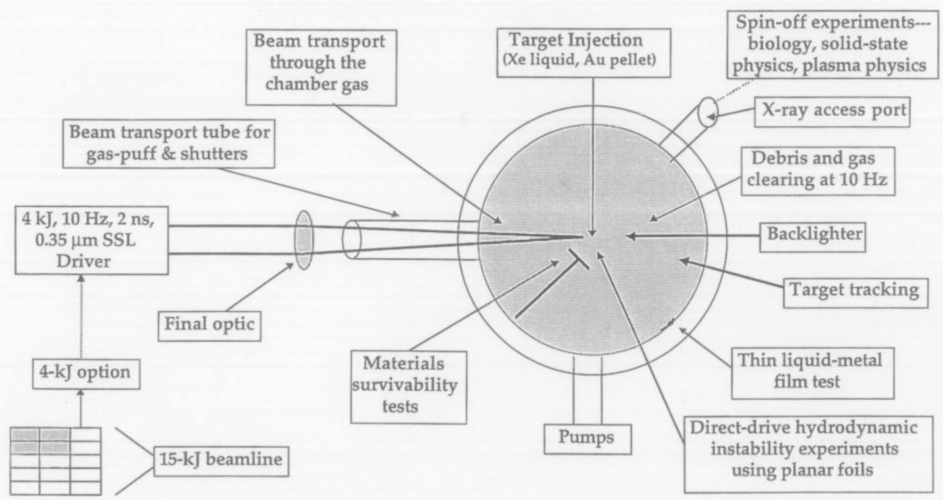

Fig. 4: Possible vision of an IRE involving kJ-class DPSSL and average-power chamber.

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